Effects of the gravivector and graviscalar fields in $N = 2, 8$ supergravity*

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Abstract

The available tests of the equivalence principle constrain the mass of the Higgs-like boson appearing in extended supergravity theories. We determine the constraints imposed by high precision experiments on the antigravity fields (gravivector and graviscalar) arising from $N = 2, 8$ supergravity.

* Accepted for publication in Phys. Lett. B. - PACS: 04.65.+e 04.80.Cc

May 1996

The discovery that $N > 1$ supergravity theories lead to antigravity is due to the work of the late J. Scherk [1, 2]. In a recent paper we have revived the interest for the implications of extended supergravity theories for antigravity [3]. This interest is connected to the high precision experiment at LEAR (CERN) measuring the difference in the gravitational acceleration of the proton and the antiproton [4]. For a review of earlier ideas about antigravity the reader is referred to the extensive article by Nieto and Goldman [5] and the references therein.

The supergravity multiplet in the $N = 2, 8$ cases contains, in addition to the graviton ($J = 2$), a vector field A^l_μ ($J = 1$). There are also two Majorana gravitini ($J = \frac{3}{2}$) for $N = 2$ [8] and a scalar field σ for $N = 8$ [1, 2]. The former fields are immaterial for our purposes and will be ignored in the following. It is also to be noted that there are important differences between extended supergravity and the Standard Model, and therefore the particles mentioned in this work should not be intended as the objects familiar from the Standard Model.

The field σ (called graviscalar in what follows) introduces a violation of the equivalence principle in the form of a universal (i.e. independent from the composition of the material) spatial dependence in Newton's constant, $G = G(r)$. However, this violation does not affect any Eötvos–like experiment measuring differences in the acceleration of bodies of different composition. Hence, the only way to constrain the effective range of the interaction mediated by the σ–field is by means of experiments testing deviations from Newton's law such as those searching for a fifth force. In contrast, the effect of the gravivector A^l_μ depends on the composition of test bodies, and is most effectively constrained by Eötvos–like experiments.

The Eötvös experiment forces upon us the assumption that the field A^l_μ have a nonvanishing mass, which may have a dynamical origin [1, 2]. In any case, the vector receives a mass through the Higgs mechanism

$$m_l = \frac{1}{R_l} = k\, m_\phi \langle\phi\rangle \ , \tag{1}$$

where $k = (4\pi G)^{1/2}$ and the mass of the Higgs–like field equals its (nonvanishing) vacuum expectation value (*v.e.v.*)

$$m_\phi = \langle\phi\rangle \ . \tag{2}$$

Thus, Scherk's model of antigravity leads to the possibility of violating the equivalence principle on a range of distances of order R_l, where R_l is the A^l_μ Compton wavelength. The available limits set by the experimental tests of the equivalence principle allow us to constrain the *v.e.v.* of the Higgs-like field ϕ, and therefore its mass. It must be noted

that the possibility of a massless field A^l_μ was already ruled out by Scherk using the Eötvös experiments available at that time [1].

In the present paper we build upon [3]: taking into account the experiments up to date, we are able to improve the limits on the gravivector A^l_μ. Moreover, we extend our treatment by considering the effects of the graviscalar for the case $N = 8$, and provide the constraints set by fifth force experiments (non Eötvos–like tests of the equivalence principle) and by the binary pulsar PSR 1913+16.

The Compton wavelength of the gravivector already obtained in [3] is of order 10 m, or less. Incidentally, the smallness of this upper bound justifies the use of Eötvos–like experimental results, which lose their validity at much larger distances. Therefore, the concept of antigravity in the context of $N = 2$ supergravity cannot play any role in astrophysics, except possibly for processes involving the strong gravity regime, i.e. near black holes or in the early universe. The same conclusion applies to the case $N = 8$, owing to the results we present here, since the $N = 8$ graviscalar and gravivector effective ranges of interaction are constrained, respectively, to be less than 100 m and 1 m.

A caveat concerning our results for the graviscalar is worth mentioning: our analysis and conclusions for the interaction of this field with matter and antimatter are by no means exhaustive, and our experimental limits hold only for the field σ entering the $N = 8$ supergravity multiplet. For a treatment of the couplings of a Brans–Dicke scalar in various other models, we refer the reader to [5]. Alternatively, ultra–light pseudo Nambu–Goldstone bosons have been considered in extensions of the standard model [6] and observational constraints based on astrophysical considerations have been obtained [7].

In $N = 2, 8$ supergravity theories, the gravivector field A^l_μ couples to the fields of the matter scalar multiplet with strengths

$$g_i = \pm k\, m_i \tag{3}$$

[8] for $N = 2$ and

$$g_i = \pm 2k\, m_i \tag{4}$$

[9, 10] for $N = 8$. Here m_i are the quark and lepton masses, the positive and negative signs hold for particles and antiparticles, respectively, and $g = 0$ for self–conjugated particles. As a consequence, in the interaction of an atom with the gravitational field, the vector field A^l_μ "sees" only the particles constituting the nucleon which are not self–conjugated, while the graviton and the graviscalar (for $N = 8$) couple to the real mass of the nucleon.

For two composite particles, e.g. two atoms with masses M_1, M_2 at separation r, the potential energy reads

$$V(r) = -\frac{GM_1M_2}{r}\left[1 + \alpha_l \exp(-r/R_l) + \alpha_\sigma \exp(-r/R_\sigma)\right] \ , \tag{5}$$

where

$$\alpha_l = -\frac{M_1^0 M_2^0}{M_1 M_2}\,\eta \ , \qquad \alpha_\sigma = \eta - 1 \ , \qquad \eta = \begin{cases} 1 & , \quad N = 2 \\ 4 & , \quad N = 8 \end{cases} \tag{6}$$

and R_l (R_σ) is the Compton wavelength of the gravivector (graviscalar). The masses in (5), (6) are given by

$$M = Z(M_p + m_e) + (A - Z)M_n \ , \tag{7}$$

$$M^0 = Z(2m_u + m_d + m_e) + (A - Z)(m_u + 2m_d) \ , \tag{8}$$

where Z and A are the atomic and mass numbers and M_p, M_n, m_e, m_u and m_d are the proton, neutron, electron, up quark and down quark masses, respectively. We use the values $m_u = 5.6$ MeV, $m_d = 9.9$ MeV, consistently with [3]. Notice that in the case $N = 8$, α_σ is three orders of magnitude larger than α_l. In fact, substituting the values of the masses in eqs. (7), (8) one obtains

$$\frac{M^0}{M} = \frac{-3.8Z + 25.4A}{-0.8Z + 939.6A} \leq \xi \ , \tag{9}$$

where $\xi = 2.7 \cdot 10^{-2}$, and the inequality $A \geq Z$ has been used. Hence, we have $|\alpha_l| \leq \eta\xi^2$ which, for $N = 8$, yields the limit $|\alpha_l| \leq 2.9 \cdot 10^{-3}$.

We consider high–precision tests of the equivalence principle and its violation induced by antigravity in $N = 2, 8$ supergravity, in order to get observational bounds on the effective range of the vector gravity interaction and the Higgs–like boson appearing in the theory [3]. The sign and the strength of the coupling of the graviscalar σ is the same for all particles and antiparticles. Since the coupling of the graviscalar is universal, the contribution of spin 0 gravity to the acceleration of a test body does not depend on its composition. Therefore, this contribution does not affect the difference $\delta\gamma$ of the gravitational accelerations of two test bodies with different compositions. When considering Eötvos–like experiments, it is safe to omit the scalar σ, and the potential for an atom in the static field of the Earth is [1]

$$V = -\frac{G}{r}\left[MM_\oplus - \eta M^0 M_\oplus^0\, f\left(\frac{R_\oplus}{R_l}\right)\exp(-r/R_l)\right] \ , \tag{10}$$

where $R_\oplus = 6.38 \cdot 10^6$ m and $M_\oplus = 5.98 \cdot 10^{24}$ kg are the earth radius and mass, respectively. The presence of the function

$$f(x) = 3 \, \frac{x \cosh x - \sinh x}{x^3} \tag{11}$$

expresses the fact that a spherical mass distribution cannot be described by a point mass located at the center of the sphere, as in the case of a coulombic potential. We describe the Earth by means of the average atomic composition $(Z_\oplus, 2Z_\oplus)$ which gives, from (7), (8)

$$M_\oplus^0 \simeq \frac{3m_u + 3m_d + m_e}{M_p + M_n} \, M_\oplus \, . \tag{12}$$

In $N = 2, 8$ supergravities, one of the scalar fields (other than σ) has a nonzero *v.e.v.* and, as a consequence, the vector field A^l_μ acquires a mass, as described by (2) (the impossibility of a massless A^l_μ being proved in ref. [1]). This leads to a violation of the equivalence principle, expressed by the difference between the accelerations of two atoms with numbers (Z, A) and (Z', A') in the field of the Earth

$$\frac{\delta\gamma}{\gamma} = \eta \, \frac{(3m_u + 3m_d + m_e)(m_e + m_u - m_d)}{M_n \, (M_p + M_n)} \left(\frac{Z'}{A'} - \frac{Z}{A} \right) f\left(\frac{R_\oplus}{R_l} \right) \left(1 + \frac{R_\oplus}{R_l} \right) \exp(-R_\oplus / R_l) \, . \tag{13}$$

In the Eötvös–like experiment performed at the University of Washington [11] (hereafter "Eöt–Wash") the equivalence principle was tested using berillium and copper and aluminum and copper. This test was used in ref. [3] to set a lower limit on the mass of the Higgs–like particle

$$m_\phi > 5 \, \eta^{1/2} \quad \text{GeV} \, . \tag{14}$$

The Eöt-Wash experiment has recently been improved [12], yielding the higher precision limit

$$\left| \frac{\delta\gamma}{\gamma} \right| \leq 3.0 \cdot 10^{-12} \tag{15}$$

for berillium and aluminum, which translates into the improved upper limit for the gravivector

$$R_l \leq 3.4 \, \eta^{-1} \quad \text{m} \tag{16}$$

or equivalently,

$$m_\phi \geq 15.8 \, \eta^{1/2} \quad \text{GeV} \, . \tag{17}$$

It is also to be noted that by increasing the factor $\left(\frac{Z'}{A'} - \frac{Z}{A} \right)$ in (13), the upper limit on R_l can be improved. This was achieved in the last version of the Eöt–Wash experiment,

where the best limit comes from the use of berillium–aluminum ($\frac{Z'}{A'} - \frac{Z}{A} = 0.038$) instead of berillium–copper ($\frac{Z'}{A'} - \frac{Z}{A} = 0.012$) or aluminum–copper ($\frac{Z'}{A'} - \frac{Z}{A} = 0.025$), which were used in the latest and in previous versions of the experiment.

We also consider the experiments aimed to detect deviations from Newton's inverse square law. In these experiments it is customary to parametrize the deviations from the Newtonian form with a Yukawa–like correction to the Newtonian potential

$$V(r) = -\frac{GM}{r}\left(1 + \alpha\,\mathrm{e}^{-r/R_l}\right) . \tag{18}$$

In the following, we assume that, in the context of antigravity, the parameter α is given by the value computed for the Eöt–Wash experiment performed using copper ($Z = 29$, $A = 63.5$) and berillium ($Z' = 4$, $A' = 9.0$), i.e.

$$\alpha = \begin{cases} 6.36 \cdot 10^{-4} & (N = 2) \\ 2.54 \cdot 10^{-3} & (N = 8) . \end{cases} \tag{19}$$

For the materials that are likely to be used in these experiments, the values of α differ from those of (19) only for a factor of order unity. Moreover, our final limits on m_ϕ depend on the square root of α. For these reasons, it is safe to use the values (19) of α in the following computations (it is to be remarked that all the experiments considered in what follows measure the gravitational attraction between bodies in a laboratory).

Equations (1) and (2) provide us with the relation

$$\frac{m_\phi(\mathrm{new})}{{m_\phi}^*} = \left(\frac{{R_l}^*}{R_l(\mathrm{new})}\right)^{1/2} , \tag{20}$$

where ${m_\phi}^* = 5\eta^{1/2}$ GeV and ${R_l}^* = 34\eta^{-1}$ m are, respectively, the lower limit on the scalar field mass and the upper limit on the Compton wavelength of the vector A^l_μ derived in ref. [3], and $m_\phi(\mathrm{new})$, $R_l(\mathrm{new})$ are the new limits on the same quantities coming from the references considered in the following.

The 2σ limits of ref. [13] (see their fig. 3) allow the range of values of R_l:

$$R_l \le 1\,\mathrm{cm} \quad , \quad R_l \ge 5\,\mathrm{cm} \tag{21}$$

for $N = 2$ and

$$R_l \le 0.5\,\mathrm{cm} \quad , \quad R_l \ge 16\,\mathrm{cm} \tag{22}$$

for $N = 8$. This corresponds to the allowed range for the mass of the Higgs–like scalar field:

$$m_\phi \le 130\,\mathrm{GeV} \quad , \quad m_\phi \ge 292\,\mathrm{GeV} \qquad (N = 2) \tag{23}$$

$$m_\phi \leq 73\,\mathrm{GeV} \quad , \quad m_\phi \geq 412\,\mathrm{GeV} \qquad (N=8)\ . \tag{24}$$

The curve A of fig. 13 in ref. [14] gives

$$R_l \leq 0.6\,\mathrm{cm} \quad , \quad R_l \geq 10\,\mathrm{cm} \tag{25}$$

for $N = 2$ and

$$R_l \leq 0.4\,\mathrm{cm} \quad , \quad R_l \geq 32\,\mathrm{cm} \tag{26}$$

for $N = 8$. Equivalently,

$$m_\phi \leq 92\,\mathrm{GeV} \quad , \quad m_\phi \geq 376\,\mathrm{GeV} \qquad (N=2) \tag{27}$$

$$m_\phi \leq 52\,\mathrm{GeV} \quad , \quad m_\phi \geq 461\,\mathrm{GeV} \qquad (N=8)\ . \tag{28}$$

The null result of the Shternberg [15] experiment reviewed by Milyukov [16] in the light of Scherk's work provides us with the limits:

$$R_l \leq 4\,\mathrm{cm} \quad , \quad R_l \geq 13\,\mathrm{cm} \tag{29}$$

for $N = 2$ and

$$R_l \leq 2.2\,\mathrm{cm} \quad , \quad R_l \geq 40\,\mathrm{cm} \tag{30}$$

for $N = 8$. These are equivalent to:

$$m_\phi \leq 82\,\mathrm{GeV} \quad , \quad m_\phi \geq 146\,\mathrm{GeV} \qquad (N=2) \tag{31}$$

$$m_\phi \leq 46\,\mathrm{GeV} \quad , \quad m_\phi \geq 197\,\mathrm{GeV} \qquad (N=8)\ . \tag{32}$$

Therefore, the best available limits on the mass of the scalar field are given by

$$m_\phi \leq 82\,\mathrm{GeV} \quad , \quad m_\phi \geq 376\,\mathrm{GeV} \qquad (N=2) \tag{33}$$

$$m_\phi \leq 46\,\mathrm{GeV} \quad , \quad m_\phi \geq 461\,\mathrm{GeV} \qquad (N=8)\ . \tag{34}$$

The experiments analyzed above also constrain the range of the graviscalar interaction for $N = 8$. The deviation from pure spin 2 gravity introduced by the gravivector and the graviscalar can be described by introducing the effective gravitational "constant" [2]

$$G_{eff}(r) = G\left[1 + \alpha_l\left(1 + \frac{r}{R_l}\right)\exp(-\frac{r}{R_l}) + \alpha_\sigma\left(1 + \frac{r}{R_\sigma}\right)\exp(-\frac{r}{R_\sigma})\right]\ , \tag{35}$$

where α_l and α_σ are given by (6). Notice that α_σ is a universal coupling constant, while α_l depends on the composition of test bodies. The binary pulsar PSR 1913+16

[17] can be used to constrain the range of the graviscalar. The upper limit (16) on the range of the gravivector prevents it from affecting the dynamics of the binary pulsar. The emission of gravitational waves from the binary occurs due to the coherent motion of mass distributions (the two neutron stars orbiting around each other) on the scale $a = 1.4 \cdot 10^9$ m (the major axis of the binary [17]), where $a >> R_l$. In the case $N = 8$, if the range of the graviscalar is $R_\sigma >> a$, one has for the binary pulsar $r \approx a$ and $\exp(-r/R_\sigma) \approx 1$ in (35). Under these assumptions, the analysis of ref. [18] can be applied (see also [5]). In order for the observed orbital decay of the binary pulsar to agree with the theory, it must be $\alpha_\sigma < 3 \cdot 10^{-3}$ [18]. This is clearly incompatible with the prescription $\alpha_\sigma = 3$ of $N = 8$ supergravity and therefore, the range $R_\sigma >> 1.4 \cdot 10^9$ m for the graviscalar interaction is forbidden by the binary pulsar observations. The case $R_\sigma \approx a$ is excluded as well using the data from the Earth–Lageos–lunar experiments summarized in fig. 1*a* of ref. [19]. The experimental constraint in this range is $\alpha_\sigma < 10^{-6}$, which is again incompatible with the prediction of $N = 8$ supergravity.

The Shternberg experiment [15] provides us with the limits on the range of the graviscalar:

$$R_\sigma \leq 0.8 \,\mathrm{cm} \quad , \quad R_\sigma \geq 14 \,\mathrm{m} \,. \tag{36}$$

By combining the data of the Shternberg and the other experiments reviewed in [16] one improves the limits (36) as

$$R_\sigma \leq 0.15 \,\mathrm{cm} \quad , \quad R_\sigma \geq 70 \,\mathrm{m} \,. \tag{37}$$

However, part of this range is already forbidden by the PSR 1913+16 data. The fifth force experiments reviewed in [19] allow only the regions

$$R_\sigma \leq 1 \,\mathrm{cm} \quad , \quad 60 \,\mathrm{m} \leq R_\sigma \leq 100 \,\mathrm{m} \quad , R_\sigma \geq 10^{14} \,\mathrm{m} \,. \tag{38}$$

The first of these limits is compatible with, but less stringent than the constraints set by the experiments in [16]. The third region is forbidden by the observational data on the binary pulsar.

As a conclusion, the best available limits on the range of the graviscalar derived from the various experiments quoted above are

$$R_\sigma \leq 0.15 \,\mathrm{cm} \quad , \quad 70 \,\mathrm{m} \leq R_\sigma \leq 100 \,\mathrm{m} \,. \tag{39}$$

The graviscalar σ, like the gravivector, cannot play any significant role in astrophysics, except possibly near black holes or in the early universe, when the size of the universe (or of primordial structures) is comparable to, or less than R_σ.

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